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Combustion characteristics, engine performances and emissions of waste edible oil biodiesel in diesel engine

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ABSTRACT

It is a good solution to produce biodiesel by using waste edible oils (WEO), such as waste cooking oils and used frying oils, due to its low cost, disposal problems and potential contamination. Therefore, WEO biodiesels has been gradually produced, and thus applied to study their effects on engine performances and emissions. However, few reviews about these studies have been published to assist understanding and popularization for WEO biodiesels so far. This paper attempts to cite and analyze highly rated journals in scientific indexes about combustion characteristics, engine power, economy, regulated emissions and non-regulated emissions of WEO biodiesels on diesel engine. The use of WEO biodiesels leads to the slight difference in combustion characteristics such as ignition delay, rate of pressure rise, peak pressure and heat release rate, and the substantial reduction in PM, HC and CO emissions accompanying with the imperceptible power loss, the increase in fuel consumption and NO_x emission on conventional diesel engines with no or fewer modification, compared to diesel. Although the inconsistent conclusions have been made on CO_2 emission of biodiesels from WEO, it reduces greatly from the view of the life cycle circulation of CO_2. For non-regulated emissions, the reduction appears for PAH emissions but carbonyl compounds emissions have discordant results for WEO biodiesels. Therefore, WEO biodiesels have the similar combustion characteristics, engine performances and emissions to that of biodiesels from food-grade oils, and the blends of WEO biodiesel with small content by volume could replace the petroleum-based diesel fuel to help in controlling air pollution, encouraging the collection and recycling of waste edible oil to produce biodiesels and easing the pressure on scarce resources to a great extent without significantly sacrificing engine power, economy and emissions.

Contents

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1. Introduction

Biodiesel, which is accepted as an attractive alternative fuel due to the depleting sources of petroleum and the environmental pollution, is produced by transesterification of vegetable oils and animal fats with an alcohol in presence of a catalyst. However, the land use for planting biodiesel feedstock based on edible plant and vegetable oil competes to that of food production. Moreover, the cost of biodiesel production from edible plant and vegetable oils is approximately one and a half times that of petroleum-based diesel depending on feedstock oils [1]. And it is reported that approximately 70–95% of the total biodiesel production cost arises from the cost of raw material such as vegetable oil or animal fats [2]. Therefore, less expensive feedstock, such as waste edible oil (WEO) including waste/used cooking oil (WCO/UCO), used frying oil (UFO) and animal fats (grease), have also been considered as alternative sources for biodiesel production [3–8].

In fact, the amount of WEO generated in the world is huge and varies according to the amount of edible oil consumed. Table 1 shows the amount of WEO generated from selected countries in the world. Moreover, management of such oils and fats pose a significant challenge because of their disposal problems and possible contamination of the water and land resources. Therefore, it is a good solution to produce biodiesel by using WEO.

Although there are an increasing number of literatures to research engine performances and its emissions when using WEO biodiesel, especially in this decade, and many researches pointed out that it might help to reduce greenhouse gas emissions, promote sustainable rural development, and improve income distribution, there still exist some resistances or doubts for using it. Of course, WEO includes higher free fatty acid and some polymerized triglycerides which increase the molecular mass and reduce the volatility of WEO. Meanwhile, WEO biodiesel has the same shortage of general biodiesel, that is, it has worse low temperature properties, greater emissions of some oxygenated hydrocarbons, higher specific fuel consumption, decrease in brake thermal efficiency and higher production cost, compared to diesel [3,17–21]. In addition, compared to general biodiesel, fatty acid esters obtained from frying oil influences the fuel characteristics (such as the viscosity and it is believed that the burning characteristics reduce) leading to a greater amount of Conradson carbon residue [22]. Table 2 shows the properties of WEO biodiesel (WCOM 100, i.e. waste cooking oil methyl esters, and WCOE 100, i.e. waste cooking oil ethyl esters), general biodiesel (RSM 100 i.e. rapeseed methyl esters), and reference diesel.

Since 2000, although there have been several literatures to make a comprehensive review about engine performances and emissions of biodiesel [3,17,23–26]. Among of them, Diyauddeen et al. [3] reviewed the performance evaluation of biodiesel from used domestic waste oils, but it is not detail in summing up the combustion, emission and engine performance. In addition, Enweremadu and Rutto [17] made a review on UCO biodiesel combustion, emissions and engine performance. However, it is regrettable that there are some errors and contradictions in this review and difficulty in reading. Moreover, this review did not include the knowledge about engine durability and non-regulated emissions. Therefore, high-quality literatures about application and study of WEO biodiesel in engine have been recollected and arranged in this article, it is helpful (1) to eliminate the environmental impacts caused by the harmful disposal of the waste oils; (2) for researchers and engine manufacturers to carry out the further studies to optimize and readjust WEO biodiesel engine and its relevant systems; and (3) for private users to understand profits for using biodiesel, and enhance consciousness of environmental protection.

2. Combustion characteristics of WEO biodiesel engine

Combustion characteristics of WEO biodiesel can be described by means of ignition delay, rate of pressure rise, peak pressure and heat release rate.

Table 1
Quantity of waste cooking oil in various countries worldwide.

Country	Quantity (million tons/year)
United States [9]	10.0
EU [10]	0.7–1.0
China [11]	4.5
India [12]	2.0[a]
Malaysia [13]	0.5
Japan [14]	0.4–0.6
Turkey [15]	0.35
Canada [16]	0.135

[a] Estimation value according to edible oil consumption in India [12].

Table 2
Properties of diesel, RSM biodiesel and WEO biodiesel [21].

	REF.	RSM 100	WCOM100	WCOE100
Density at 15 °C (kg/m^3)	834.9	883.0	887.0	878.0
Kinematic viscosity at 40 °C (cSt)	2.718	4.440	5.160	4.920
Gross heating value (MJ/kg)	45.54	39.63	39.26	39.48
Acid number (mg KOH/g)	0.085	0.030	0.550	0.270
% C (wt)	86.13	77.07	76.95	77.38
% H (wt)	13.87	12.08	12.14	12.19
% O (wt)	0	10.85	10.91	10.43
ppm S (wt)	33.9	1	0	0
Molecular weight	211.7	294.8	293.2	306.7
Stoichiometric fuel/air ratio	1/14.67	1/12.54	1/12.55	1/12.64
Iodine number	–	108.7	97.5	105.6

2.1. Ignition delay

Ignition delay is defined as the time interval between the start of injection (SOI) timing and start of combustion (SOC) timing of the fuel, and usually presented by degrees of crankshaft rotation. Ignition delay decreases with the use of most of WEO biodiesels compared to the diesel fuel. Ozsezen et al. [27] found that the ignition delays for WPOME (waste palm oil methyl ester), COME (canola oil methyl ester) and PBDF (petroleum-based diesel fuel) were calculated 7.50 °CA, 8.00 °CA and 8.25 °CA, when authors studied the performance and combustion characteristics of a 6-cylinder, 4-stroke, water-cooled (WC), direct injection (DI), naturally aspirated (NA) diesel engine at the constant engine speed mode (1500 rpm) under the full load condition of the engine. Rao et al. [28] studied the combustion, performance and emission characteristics of used cooking oil methyl ester (UCME) and its blends with diesel fuel in a single cylinder, 4.4 kW, air-cooled (AC), DI diesel engine with constant speed, and observed that the ignition delay of UCME and its blends are significantly lower than that of diesel. Ozsezen and Canakci [29] investigated the exhaust emission of a 4-cyclinder, 4-stroke, WC, NA, IDI (indirect injection) and unmodified diesel engine fueled with methyl ester of waste frying palm oil and its blends with PBDF at the full load—variable speed condition, and reported that the ignition delays slightly decreased by the increase of biodiesel in the fuel blend. It was reported in [30] that the ignition delay for pure YGME (yellow grease methyl ester) biodiesel were shorter about 0.63 °CA than that of No. 2 diesel fuel, when authors investigated the effect of the biodiesel from fat-based yellow grease with high free fatty acid at steady-state engine operating conditions in a four-cylinder turbocharged diesel engine. However, Sudhir et al. [31] reported the increase in ignition delay due to the lower cetane index of WCO biodiesel compared to the reference diesel fuel.

The decrease in ignition delay for WEO biodiesel is mainly attributed to the higher cetane number of WEO biodiesel compared to the reference diesel fuel [27–36]. It is known that the fuels with high cetane number makes auto-ignition easily and gives short ignition delay. Rao et al. [28] further explained that Oleic and Linoleic fatty acid methyl esters in the UCME split into smaller compounds when it enters the combustion chamber resulting in higher spray angles and hence caused earlier ignition. Besides, this decrease is considered as the result of the less amount of aromatic compounds of WEO biodiesel compared to diesel fuel, because the ignition delay increase with increasing aromatic compounds in the fuel [37].

Engine speed, engine load, distillation temperature of WEO biodiesel and WEO biodiesel content have effect on ignition delay with the use of WEO biodiesel [28,29,33,36,38]. In the literature [29], authors illustrated the ignition delays of B100 biodiesel from waste frying palm oil and diesel versus engine speeds. The higher ignition delay timing appears with the increase in engine speed, but it is lower than that of PBDF at every speed point. Stringer et al. [36] also observed that the ignition delay for all fuels including B100 YGME biodiesel and its blends fuels (B50, B20 and B5) increased with the increase of engine speed. Authors in [28,33,34] reported that the reduction in ignition delay increases with the increase in load for all test fuels. This may be due to higher combustion chamber wall temperature and reduced exhaust gas dilution at higher loads. Sabagh et al. [38] claimed that, compared to diesel, the higher distillation temperature of biodiesel from the waste frying oil may shorten the ignition delay of the fuel and it decreases the probability of the occurrence of knocking in the diesel engine. In [28,34], authors illustrated the trend that the less ignition delay timing for WEO biodiesel with the increase of biodiesel content in blends fuels. This trend is agreed by Stringer et al. [36], who observed that the ignition delay slightly decreased with the increase of biodiesel in the blends including B5, B20, B50 and B100 fuels.

2.2. SOI timing and injection line pressure

The SOI timing has an important impact on in-cylinder pressure, combustion efficiency, and exhaust gas emissions. Usually, the SOI timing is determined from the fuel injection line pressure data.

The SOI timing for WEO biodiesel is earlier than that of PBDF. Stringer et al. [36] found that, when test was implemented in a four-cylinder, NA, IDI diesel engine with mechanically controlled distributor type injection pump, the SOI timings for B100 from used frying palm oil were 1.12 °CA, 1.21 °CA, 0.66 °CA, 0.81 °CA, and 2.14 °CA earlier than that of PBDF at 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm, and 3000 rpm, respectively. Canakci and Van Gerpen [30] measured that the SOI timings for the pure YGME biodiesel, 20% YGME biodiesel blend and No. 2 diesel are 17.05 °CA BTDC, 14.60 °CA BTDC, 13.50 °CA BTDC, respectively. Ozsezen et al. [27] reported that, when they experimented the combustion characteristics of WPOME and COME biodiesels in a DI diesel engine with mechanically controlled in-line type injection pump, at the constant engine speed mode (1500 rpm) under the full load condition, the test engine was fueled with biodiesels, the SOI timing for WPOME and COME is 0.75 °CA and 1.25 °CA earlier than that of PBDF, respectively. This trend is also agreed by Çetinkaya and Karaosmanoğlu [39], who conducted the engine performance and emission tests with single cylinder, 4-four, 9 kW, 3 LD 510 coded diesel engine and generator set including 1-cylinder, 10.5 kW, 4 LD 640 coded diesel engine fueled with used cooking oil biodiesel.

The comparison of the injection line pressure for WEO bio diesel and diesel versus crank angle degree was illustrated in [27,30,36], since the fuels' physical properties were different and different quantities of fuel were injected. It was shown that biodiesel and diesel have different injection line pressures, although with a similar pattern. However, the authors in [29,40] conducted the comparison of the injection pressure of WEO biodiesel and diesel versus engine speed, the former showed the slight lower injection pressure for biodiesel compared to diesel almost over the engine speed condition, the later showed the similar pressure between the tested fuels due to the common rail system. Unbelievable, they showed the reverse trend of injection pressures versus engine speed.

Biodiesel properties, such as density, viscosity and compressibility, have to do with the earlier SOI timing. Ozsezen et al. [27] and Stringer et al. [36] firstly contributed to the higher density of biodiesel, and the higher viscosity of biodiesel, which leads to the reduced fuel losses during the injection process, the faster evolution of pressure and thus the advanced injection timing. Furthermore, they explained that the lower vapor content in a high pressure injection system could also be the reason for the advanced injection timing. By decreasing the vapor volume, the injection delay decreases which results in advanced injection timing. In addition, other possible reason is the lower compressibility of biodiesel compared to diesel, with the same fuel pump at the same speed. Canakci and Van Gerpen [30] agreed that fuel properties such as the compressibility and speed of sound affected the SOI timing.

It is seemed that engine speed affect SOI timing and injection pressure of WEO biodiesel. In the literature [36], as mentioned above, the earlier SOI timings for B100 from used frying palm oil were different at different engine speeds. Also, the injection pressure for B100 appeared different at different engine speeds, according to the illustrations. Çetinkaya et al. [40] showed the

trend of the reduction in injection pressure with the increasing of engine speed. However, Çetinkaya and Karaosmanoğlu [39] and Ozsezen and Canakci [29] illustrated the reverse trend of the increase in injection pressure with the increasing of engine speed.

2.3. Heat release rate and the start of combustion timing

Heat release pattern of a fuel is helpful to get some information about the combustion process in an engine, such as the start of combustion (SOC) timing and heat release rate in different combustion stages. In addition, it favors the analysis of NO_x formation inside the combustion chamber and the cooling system requirements of the engine.

The SOC timing is defined as the point at which the first change in slope occurred in the heat release rate. The advance in SOC timing appears in engine with WEO biodiesel, compared to diesel. Canakci and Van Gerpen [30] obtained that the SOC timing of pure YGME biodiesel was earlier about 4.2 °CA than that of the No. 2 diesel fuel, when authors tested in a John Deere 4276T diesel engine at full load with the engine's peak torque condition. Ozsezen et al. [27] measured that the SOC timing of the WPOME and COME was taken place at 9.75 ° CA BTDC, while the SOC timing in the case of PBDF was occurring at 7.25 °CA BTDC. The SOC timing is the cumulative effect of differences in the start of injection and changes in the ignition delay period [30], and is affected by oxygen content and cetane number of biodiesel [27].

The earlier premixed combustion phase was completed by biodiesel and its blends with regard to PBDF, due to their earlier start of combustion and having a less premixed combustible mixture [36]. Lapuerta et al. [41] clearly observed the pre-combustion for biodiesel during modes C′ and H, by using a 4-cylinder, 4-stroke, turbocharged, intercooled, direct injection 2.2 L Nissan engine. The authors in [36] further pointed out that the lower rate of premixed burning for biodiesel as the result of the lower volatility of biodiesel compared to PBDF. Biodiesel vaporizes more slowly than PBDF and contributes less to premixed combustion. Also, because of the shorter ignition delay, the time for occurrence of the maximum heater lease is earlier for biodiesel or its blends in comparison with PBDF. Ozsezen et al. [27] also contributed the less premixed combustion of biodiesel to the slower vaporization of biodiesel. In addition, Rao et al. [28] recorded the maximum heat release rate of 51.481 J/(Deg. CA) for UCME at 8° BTDC and the maximum heat release rate of 71.459 J/(Deg. CA) for diesel at 6° BTDC.

However, Lapuerta et al. [41] concluded that the calculation of the heat release fraction from the in-cylinder pressure signal through the diagnostic model led to no differences in combustion timing and very slight differences in the premixed peak of the rate of heat release for the two biodiesel fuels of WCOME (waste cooking oil methyl ester) and WCOEE (waste cooking oil ethyl ester), their blends with diesel fuel and diesel fuel. Although the cetane numbers of the fuels tested could not be measured, these diagrams show similar auto ignition behavior in all cases.

The less ignition delay was regarded as the result of the lower heat release rate of UCOME and its diesel blends [28]. Also, lower calorific value of UCOME and its blends may contribute to lower heat release [42].

The oxygen content of fuels and the engine speed and load have impact on the heat release pattern [28,32–34,36]. Stringer et al. [36] showed that an increase in the oxygen fraction of the injected fuel provides an increase in the maximum heat release rate and in the fraction of fuel burned in the premixed combustion phase; this case is more obvious at a high engine speed. Rao et al. [28] reported that as the percentage of UCME in the blend increases, the maximum heat release rate decreases and the crank angle at which it takes place advances. In [32], the authors compared the heat release rate for TD50 (the treated waste cooking oil biodiesel–diesel blend with 50/50 by volume) and diesel at the load of 25%, 50% and 75%. The maximum heat release rate increases with an increase in engine load from the low to medium load, but decreases at high load for all fuels, and the maximum heat release rate occurs slightly closer to the TDC with increase of engine load.

2.4. Cylinder gas pressure and rate of pressure rise

2.4.1. Cylinder gas pressure

In a CI engine, cylinder pressure depends on the burned fuel fraction during the premixed burning phase, i.e. initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. The pressure waves in the cylinder during combustion indicate engine noise. High peak pressure and maximum rate of pressure rise correspond to large amount of fuel burned in premixed combustion stage.

Authors in [27] mentioned above observed that both pure WPOME and COME biodiesels had no trace of pressure waves and the cylinder gas pressure smoothly varied at 1500 rpm under the full load condition. Nonetheless, the cylinder gas pressure of the PBDF fuel as a reference fuel varied unsmoothly compared to the biodiesel. And the peak cylinder gas pressures of the biodiesels are higher than that of the PBDF. The peak cylinder gas pressure for WPOME and COME was measured 8.34 MPa and 8.33 MPa at 6.75 °CA ATDC, while the peak cylinder gas pressure for PBDF was 7.89 MPa occurring at 7 °CA ATDC. Stringer et al. [36] found that the maximum gas pressure did not show any significant difference among the fuels including the B100 from used frying palm oil, B50, B20, B5 and PBDF over the speed range. The maximum cylinder gas pressure occurred within the range of 2.5°–6 °CA ATDC for all tested fuels, but the peak of cylinder gas pressure slightly closed to top dead center for biodiesel or its blends compared to PBDF. In the maximum torque condition of 2000 rpm, the peak cylinder gas pressure for B100 was 8.79 MPa occurring at 2.75 °CA ATDC, while the peak cylinder gas pressure in the case of PBDF was 8.73 MPa occurring at 3.5 °CA ATDC. Rao et al. [28] also reported that UCME and its blends follow the similar pattern of pressure rise to that of diesel at all load conditions, and the peak pressure is slightly higher for pure UCME biodiesel compared to that of diesel.

The higher BSFC amounts, cetane number, boiling point, oxygen content and advance in the SOI timing are considered as the result of the higher peak cylinder pressure of pure WPOME and COME biodiesels compared to PBDF [27]. Especially, they pointed out that the oxygen content of the biodiesels increases fuel–air mixing rate in the cylinder compared to the PBDF and then cause to extend the combustion duration, which is also agreed by Rao et al. [28]. In addition, Rao et al. [28] contributed the slightly higher peak pressure of pure UCME biodiesel to the lower ignition delay of biodiesel.

On the other hand, Sudhir et al. [31] observed the lower peak pressure for WCO biodiesel and contributed to the poor combustion of biodiesel due to the increase in ignition delay as the result of lower cetane number of biodiesel compared to the diesel fuel. Muralidharan et al. [34] showed the variation of cylinder pressure with crank angle for diesel, 20%, 40%, 60% and 80% WEO biodiesel with diesel at an engine speed of 1500 rpm on a single cylinder, 4-stroke engine, and observed that peak pressures of 67.84 bar, 66.22 bar, 49.61 bar and 49.59 bar has been recorded for standard diesel, B20, B40, B60 and B80, respectively. It should be noted that, it is self-contradictory in the literature [17], because the authors considered the higher peak pressure for UCO biodiesel, but they quoted the exmaple of lower peak pressure for UCO biodiesel.

Engine load, engine speed and biodiesel percentage have impact on the peak cylinder gas pressure of WEO biodiesel engine. From the literature [28], the peak cylinder gas pressure for pure UCME biodiesel becomes higher with the increasing of brake power. According to illustration in the literature [36], the trend that the peak cylinder gas pressure for B100 increases with the increasing of engine speed can be observed. The effect of biodiesel percentage was shown in [28,43]. But both Rao et al. [28], who tested by using 20%, 40%, 60%, 80% and 100% UCME biodiesel, and Peterson et al. [43], who investigated with the use of 25%, 50% and 100% HySEE biodiesel, illustrated the big variation of the peak cylinder gas pressure with the increasing of biodiesel content.

2.4.2. Rate of pressure rise

The rate of pressure rise for diesel is higher compared to those of UCME and its blends, which is reported by Rao et al. [28]. This is due to the longer ignition delay and shorter combustion duration of diesel compared to UCME and its blends. Also the premixed combustion heat release is higher for diesel which may be responsible for higher rate of pressure rise. This argument is agreed by Ozsezen and Canakci [29].

2.5. Summary

Based on analysis above, the following conclusions are available:

(1) Ignition delay decreases with the use of most of WEO biodiesels due to higher cetane number of WEO biodiesel compared to the diesel fuel. Engine speed, engine load, distillation temperature of WEO biodiesel and WEO biodiesel content have effect on ignition delay with the use of WEO biodiesel.
(2) SOI timing for WEO biodiesel is earlier than that of PBDF due to higher density, higher viscosity and lower compressibility. WEO biodiesel and diesel have different injection line pressure due to different physical properties of fuel and different quantities of fuel injected. Engine speed affects SOI timing and injection pressure of WEO biodiesel.
(3) The advance in SOC timing and the lower heat release rate appears in engine with WEO biodiesel, compared to diesel. The SOC timing is the cumulative effect of differences in the start of injection and changes in the ignition delay period, and is affected by oxygen content and cetane number of WEO biodiesel. The lower heat release rate is contributed to the less ignition delay and the lower calorific value of WEO biodiesel. Oxygen content and engine speed have impact on the heat release pattern.
(4) The peak cylinder gas pressure of WEO biodiesel are slightly higher than that of the PBDF, resulting from the higher BSFC, cetane number, boiling point, oxygen content and advance in the SOI timing. Engine load, engine speed and biodiesel percentage have impact on the peak cylinder gas pressure of WEO biodiesel engine. The rate of pressure rise for diesel is higher compared to those of WEO biodiesel, due to the longer ignition delay and shorter combustion duration of diesel.

Table 3
Results of combustion characteristics of WEO biodiesel compared to diesel.

Combustion characteristics	Comparison result
Ignition delay	Lower
SOI timing	Advance
Injection line pressure	Different
Heat release rate	Lower
SOC timing	Advance
Peak cylinder gas pressure	Slightly higher
Rate of pressure rise	Higher

Table 3 shows that the results of combustion characteristics for WEO biodiesel compared to diesel.

3. Engine performances of WEO biodiesel engine

Engine performance characteristics are the major criterion that governs the suitability of a fuel. This work is concerned with the review about power performance (engine power and engine torque), fuel consumption, thermal efficiency when using of WEO biodiesel fuel.

3.1. Power performance

More or less reductions in power performance for pure biodiesel from WEO are reported in most of researches [27,29,36,39,40,44–52]. For example, An et al. [44] reported that the average reductions from 1600 rpm to 3600 rpm is 12.2% for B100 derived from waste cooking oil on a common-rail injection diesel engine, compared to ultra low sulfur diesel. The methyl ester from waste frying oil (WFOME) was tested by Utlu and Koçak [47] in a 4-cylinder, TC and DI diesel engine, and the authors observed that the average decrease of torque and power values was 4.3% and 4.5% for WFOME, respectively, compared to No. 2 diesel, although the maximum torque and power values of biodiesel decrease as 1.45% and 0.55%, respectively. And Çetinkaya et al. [40] found that the torque and brake power output obtained during the used cooking oil originated biodiesel applications are 3–5% less than those of No. 2 diesel fuel. However, the more reductions in power performance for WEO biodiesel were reported in [50], where the maximum power loss for pure biodiesel from used cooking oil is more than 12.5% at rated speed compared to diesel. Especially, in [51], the observed maximum brake power with traditional diesel is 25% higher than that with biodiesel from waste cooking oil and 52% higher than that of the biodiesel with glycerine at 2500 rpm.

Less decrease in engine power and torque are elusioned in [27,39,52]. Ozsezen et al. [27] reported that the maximum brake torque for PBDF, WPOME and COME at 1500 rpm under at full load condition was measured as 328.69 N m, 320.24 N m and 319.80 N m, respectively. The maximum brake power (52.12 kW) was obtained for PBDF, followed by WPOME (50.78 kW) and COME (50.71 kW). In [39], a small decrease in the range of 0.8% and 0.66% was observed for engine power as a result of B100 from used cooking oil and B20 applications when compared to No. 2 diesel fuel. And Roskilly et al. [52] found that the differences of the engine power outputs when fuelled with two types of fuels (pure biodiesel from recycled cooking fat and vegetable oil, and diesel) were all less than 1% over the whole test range. Especially, it was illustrated that there are almost no loss of torque for all tested fuels, when WCOM100, WCOM70, WCOM30, WCOE100, WCOE70, WCOE30 and the reference diesel fuel were tested in a 4-cylinder, 4-stroke, TC, intercooled, DI, 2.2L Nissan diesel engine in [41], and two different pure biodiesels (B1and B2) from used cooking oil, and the blends fuels (B1_70, B1_30, B2_70, B2_30) and the reference diesel were tested in [13].

The loss of power performance for WEO biodiesel usually is explained mainly as the result of the lower heating value [40,47,48], higher density and viscosity [47], which lead to fuel

flow problems, decrease combustion efficiency and lower thermal efficiency compared to diesel fuel.

On the other hand, Al-Widyan et al. [53] reported the higher brake power output for all the test fuels including 100%, 75%, 50%, 25% WVO (waste vegetable oil) biodiesel blends relative to the baseline fuel, with the test of a single-cylinder, DI, NA, WC engine coupled to an electric dynamometer. They contributed to the higher fuel mass flow of the denser, resulting in larger mass flow, and more viscous blends, resulting in less internal leakage in the fuel pump. Usta et al. [54] also found that, even if addition of the biodiesel to the diesel fuel decreases its heating value, higher power for biodiesel from a hazelnut soapstock/waste sunflower oil mixture and its blends (100%, 75% and 50%) was obtained in a 4-cylinder, TC, IDI diesel engine, due to higher oxygen (10%) for blends leading to more complete combustion, the larger mass flow rate for blends, and the more viscous for blends meaning less internal leakage in the fuel pump.

Of course, Gonzalez-Gomez et al. [55] found the different trend of power performance characteristics, that is, the power developed by WCOME was higher (approximately 9%) than that for mineral diesel fuel at low speeds (under about 4800 rpm), but it was lower at higher speeds (above about 4800 rpm). They concluded that the WCOME had better power performance characteristics than mineral diesel fuel at low speeds, although they had no explanation about this trend.

The effect of WEO biodiesel percentage on engine power performance was investigated in [29,36,43,44,48,50,54]. Among of them, Canakci et al. [48] reported that the predicted values for the brake torques decreased with the increasing amount of biodiesel in the fuel blend, when the biodiesel blends from waste frying palm oil (B100, B50, B20, B5) were used to measure and predict the engine performance and exhaust emissions in a 4-cylinder, 4-stroke, NA, WC, IDI and 1.8 VD diesel engine with different engine speeds at full load conditions. The same trend can be found in [36,43,44,50]. However, Usta et al. [54] illustrated that the power initially increases with the addition of biodiesel due to higher oxygen content for more complete combustion, a larger mass flow rate and less internal leakage, reaches a maximum value, and then decreases with further increase of the biodiesel content due to the lower heating value and the higher viscosity, which cause slightly poorer atomization and poorer combustion.

Engine power output depending on engine speed was shown in [12,13,29,36,39–41,44,47,48,50,51,53–57]. Except that there was significantly different trend for biodiesel from waste vegetable oils and the diesel in [53], all of them showed the almost same trend versus engine speed for WEO biodiesels and diesel fuels.

The effect of engine load on engine power performance was illustrated only in [54]. As the load decreases, generated power by D82.5/B17.5 biodiesel blend fuel decreases at the same engine speed, and there is the similar trend between bioidesel fuel and diesel.

Glycerin content influences power performance for biodiesel. Özkan et al. [51] investigated the effect of waste cooking oil biodiesel fuels with and without glycerine on CI engine performance, and reported that glycerine has a negative effect on engine power performance. This argument is also verified by Davis et al. [57], who compared the effects of ultralow sulfur petroleum diesel to B5 and B20 blends of both BQ9000 certified biodiesel from recycled cooking oils and non-BQ9000 certified biodiesel on engine performance, efficiency and NO_x emissions using a single cylinder Yanmar diesel engine. Results showed that non-BQ9000 certified biodiesel causes the worse power performance due to the higher glycerin content compared to BQ9000 certified biodiesel. The author pointed out particularly that the engine would not run when fueled with non certified B50 or B100 due to filter plugging and injector fouling.

3.2. Economy performance

Engine fuel consumption increases when using WEO biodiesel with regard to diesel, which is agreed in most of researches [11–13,18,27–31,36,39–42,45,47–54,56,58–65]. For example, Çetinkaya and Karaosmanoğlu [39] reported that the brake specific fuel consumption (BSFC) for B100 and B20 are higher than that of diesel fuel in the range of 10% and 4%, respectively. [63] found that the average specific fuel consumption increased by $12.73 \pm 0.03\%$ for B100 from waste frying palm oil while that of B50 showed an increase of $5.60 \pm 0.02\%$ with respect to diesel No. 2. Utlu and Koçak [47] presented that average brake-specific fuel consumption for usage of WFOME is 14.34% higher than diesel fuel. And Roskilly et al. [52] reported that the biodiesel consumptions increased by 14.5–20.9%, respectively, for the Nanni engine over the load range compared to that when fuelled with fossil diesel. However, some researchers revealed a slight increase in BSFC. For example, Ozsezen et al. [27] found that the BSFC for WPOME and COME is 7.48% and 6.18% higher than that of PBDF, respectively. And Ulusoy et al. [49] observed that biodiesel consumption was 2.43% less than that of no. 2 diesel fuel. Of course, it was reported in [66] that there is very similar fuel consumption for WEO biodiesel and diesel.

However, the authors [34] illustrated that the BSFC of the blends B20, B40 and B60 were lower than that of standard diesel, while the BSFC of the blend B80 was almost same to that of diesel. Tests were conducted with a single cylinder at an engine speed of 1500 rpm and different loading conditions.

The higher brake specific fuel consumption of a WEO biodiesel engine is considered as the result of the lower heating value [11,13,29,30,36,39–41,49,52,54,56,60,62,63,67,68], the higher density [27,29,36,54] and the higher viscosity [27,54] for biodiesel compared to diesel.

WEO biodiesel percentage in blends influences engine economy performance [12,18,29,30,36,43,48]. For example, Stringer et al. [36] found that, on average, BSFCs of B100, B50, B20, and B5 were 16.76%, 9.42%, 5.78%, and 2.17% higher than that of PBDF, respectively, over the whole speed range, the BSFC slightly increased with the increase of biodiesel percentage in the fuel blend. Also, it is clearly shown that the BSFC increase with the increase of biodiesel percentage in the fuel blends, according to BSFC values for ULSD, blend-1, blend-2, blend-3, blend-4, and pure biodiesel from waste cooking oil in [62]. This trend was also reported in [29,48]. However, in [12], authors showed the fuel consumption with various fuels blend percentage, the mean value of engine specific fuel consumption of 10%, 20%, 30%, 40% and 50% blends for various engine speeds are 4.0%, 0.8%, 0.6%, -2.2% and 1.4% higher than diesel fuel, respectively.

The effect of engine speed on fuel consumption of WEO biodiesel is reported in [12,29,36,48,51,53,54,56,60]. Stringer et al. [36] claimed that there is the same trend for all tested fuels including biodiesel from used frying palm oil and PBDF, that is, by increasing the engine speed from 1000 rpm to 2000 rpm, the fuel consumption for all tested fuels decreased due to the increase in atomization ratio. From 2000 rpm to 3000 rpm, the fuel consumption for the fuels increased due to the decreasing of volumetric efficiency. The same trend was illustrated in [12,29,48,51]. But in the literature [56], the BSFC values of the three fuels (ASTM D2 diesel, waste cooking oil biodiesel, marine fish oil biodiesel) are shown to decrease with an increase in engine speed varied from 800 rpm to 2000 rpm. However, Lin and Lin [60] reported that the increase of engine speed from 1000 rpm to 2200 rpm raised the BSFC for biodiesel and diesel, and as the rate of increase

of fuel consumption is larger than that of engine power output with the increase of engine speed, a rising trend of BSFC should appear. Especially, Al-Widyan et al. [53] shows that the difference in BSFC between the diesel fuel and the pure biodiesel from waste vegetable oil increased with engine speed. The authors contributed to poor mixture preparation of biodiesel, particularly less evaporation of the heavier blends at lower engine speeds.

The effect of engine load on fuel consumption of WEO biodiesel is reported in [11,18,28,31,45,54,61–63]. Jain et al. [61] observed that, when they tested a engine coupled with 2KVA alternator and loaded by electrical resistance, the BSFC decreases as the load increases for diesel, biodiesel from waste cooking oil and the blends (10%, 20%, 30%, 40%, 50%), but the more reduction in BSFC appears at low load. They contributed this trend to the increased cylinder wall temperature at high load, which reduces the ignition delay thus to improve combustion and reduce fuel consumption. The same trend was reported in [11,28,31,54,62]. However, a different trend was found in [63], where the authors showed the specific fuel consumptions for diesel, WFPOEE and 50% WFPOEE at different electrical loads, 25 kW, 50 kW and 75 kW, respectively. The lowest specific consumption value was observed at the electrical load of 50 kW for all tested fuels.

Biodiesel including some residues, such as glycerine, acid or water, etc., was investigated experimentally to compare the effect on BSFC. Davis et al. [57] found the non-BQ9000 certified biodiesel from waste oil and grease caused the worse engine economy due to impurity and higher glycerin content compared to BQ9000 certified biodiesel, the higher percentage of non-BQ9000 biodiesel leads to the worse engine economy. Özkan et al. [51] also reported that glycerine has a negative effect on engine economy when the waste cooking oil biodiesels with and without glycerine were compared. Cheng et al. [18] compared the B20 biodiesel mixed the diesel with 20% crude biodiesel with some methanol and impurities and B20' biodiesel including 20% refined biodiesel and the diesel, and found that the minimal fuel consumption for the diesel, B20′ and B20 was 203.4 g/(kW h), 205.4 g/(kW h) and 210.7 g/(W h), respectively.

3.3. Brake thermal efficiency

Brake thermal efficiency (BTE) is defined as the actual brake work per cycle divided by the amount of fuel chemical energy as indicated by the fuel's lower heating value. If different fuels are compared, brake thermal efficiency is more suitable instead of specific fuel consumption.

Compared to diesel fuel, the thermal efficiency for WEO biodiesel decreases slightly or appears similar [13,27,28,30,31,36,41,42,45,48,51,54,61,63]. Stringer et al. [36] showed that the brake thermal efficiency for PBDF, B100, B50, B20, and B5 over the speed range at the full load condition. At 2000 rpm, the maximum brake thermal efficiencies for B100 and PBDF were calculated as 24.44% and 25.76%, respectively. The lower decrease in thermal efficiency for WEO biodiesel was reported in [27,28,31,61]. For example, Rao et al. [28] obtained that the BTE of UCME is lower than that of diesel by 2.5% at rated load. It is observed that the thermal efficiency of the WCO biodiesel is marginally less by 1–1.85% compared to base line diesel in [31]. Lertsathapornsuk et al. [63] reported that the engine efficiencies of the generator powered by biodiesel were similar to those powered by diesel No. 2 at all levels of electrical loads. The average engine efficiencies of the engine powered by B100 and B50, at 50 kW load, were slightly lower than diesel No. 2 by $0.26 \pm 0.03\%$ and $0.24 \pm 0.02\%$, respectively.

The thermal efficiency of a diesel engine is inversely proportional to its BSFC and the heating value of the fuel. Therefore, BSFC and heating value of WEO biodiesel directly influence BTE. However, other properties and characteristics of biodiesel also affect BTE, such as higher viscosity leading to minimizing the fineness of atomization [31,61], lower cetane index [31], higher cetane number [61,63], smaller ignition delay [28], lower heating value [27,54], higher oxygen content [42,61,62] resulting in complete combustion, higher lubricity which reduce friction loss [62], higher BSFC [27].

However, some literatures [11,50,53,62] reported the increased thermal efficiency for WEO biodiesel compared to diesel. It is observed in [11] that the ULSD, despite having lower BSFC, has the lowest brake thermal efficiency compared to pure biodiesel from waste cooking oil, the biodiesel with 10% blended methanol and 10% fumigation methanol on a 4-cylinder NA DI diesel engine operating at a constant speed of 1800 rpm with five different engine loads. The maximum attained brake thermal efficiencies are 37.2%, 39.1%, 39.6% and 37.5%, respectively, for the ULSD, biodiesel, biodiesel with 10% fumigation methanol and biodiesel with 10% blended methanol. Di et al. [62] illustrated by using experimental data that the BTE of biodiesel from waste cooking oil and its blends is increased compared to diesel at the test load of 0.08 MPa, 0.20 MPa, 0.38 MPa, 0.55 MPa and 0.67 MPa. The higher BTE for pure WEO biodiesel was also reported in [50,53].

The increasing trend is attributed to the higher oxygen in biodiesel which improves combustion [11,62], and the higher lubricity of biodiesel which reduce friction loss [62].

The effects of biodiesel content, engine speed, engine load and additives have been investigated. Canakci et al. [48] showed that the thermal efficiency decreases with increasing ratio of the biodiesel in the fuel blend, when they tested the PBDF, B10, B30, B40, B60, B80 and B100 from waste frying palm oil in a 1.8 VD diesel BMC engine with a fixed load. Lertsathapornsuk et al. [63] illustrated the same trend at low and medium loads when 100% diesel, 50% biodiesel and 100% biodiesel from waste frying palm oil were tested in a 100 kW diesel generator only at the low and medium loads. In addition, the BTE for B100, B50, B20, B5 decrease with the increasing of biodiesel only after the engine speed of 2000 rpm. However, Di et al. [62] reported that, at each engine load except 0.55 MPa, the BTE increases gradually with the increase of biodiesel in the fuel, and the engine attains the maximum BTE with pure biodiesel from waste cooking oil. Of course, Rao et al. [28] found that the decrease in BTE is not proportional to the increase in UCME percentage in the fuels. And Jain et al. [61] found that the brake thermal efficiency for biodiesel for all blends range (B10–B100) was fond almost comparable to efficiency of diesel fuel.

Some authors in [36,48,51] reported that the BTE of pure WEO biodiesel increases with the increasing of engine speed, reaches the maximum value, and then decreases with the further increasing of engine speed. But in [54], there are the different change trends for D82.5/B17.5 biodiesel blend fuel at 50%, 70% and 100% loads.

It is reported that the BTE of WEO biodiesel increases with the increasing of engine loads [11,28,61,62]. However, Lertsathapornsuk et al. [63] obtained that, over the whole engine load range of 20–70 kW, the highest engine efficiency was observed at the electrical load of 50 kW.

Özkan et al. [51] investigated the effect of glycerine in biodiesel on the BTE, and illustrated that, at low loads, the biodiesel with glycerine has the higher efficiency than that of biodiesel due to the low SFC, and gives the lower efficiency due to the high SFC at medium and high loads. Especially, there is a significant decrease in the efficiency value of biodiesel with glycerine at 3000 rpm. Davis et al. [57] reported that, there existed a significant difference between certified biodiesel blends (B5C and B20C) and non-certified biodiesel blends (B5NC and

B20NC) for thermal efficiency. Analysis revealed that B5NC had a significantly lower thermal efficiency than all fuels other than B20NC. B20C had a higher thermal efficiency than all fuels other than.

Meng et al. [11] found that, when the engine is operating on biodiesel with 10% by volume of fumigation methanol (10% fumigation fuel), this fuel gives better efficiency at medium and high engine loads compared to pure biodiesel, due to rich mixture resulting in better combustion, while this fuel gives slightly lower efficiency at low engine loads, due to lean mixture. The authors also found that, when the engine is operating on biodiesel mixed with 10% by volume of methanol, this type fuel gives the opposite trend for BTE as that of the 10% Fumigation fuel, compared to biodiesel. They explained that the addition of methanol leads to decrease in the viscosity and the cetane rating of the blended fuel and an increase in the latent heat of evaporation. Therefore, the methanol will increase the ignition delay, leading to a larger percentage of fuel burned in the premixed mode. This will lead to increase in the brake thermal efficiency. On the other hand, the methanol in the fuel will tend to lower the combustion temperature, leading to a decrease in the brake thermal efficiency. At low engine load, only a small amount of fuel is burned and the fuel is burned mainly in the premixed mode. The first factor tends to dominate, leading to an increase in the brake thermal efficiency. At medium and high load, with an increasing amount of fuel injected into the engine, the second factor tends to dominate, leading to a decrease in the brake thermal efficiency.

3.4. Endurance performance

A few authors investigated the endurance performance for WEO biodiesel on the basis of wear and carbon deposits of vital parts of engine.

Çetinkaya et al. [40] investigated the engine performance and the road performance of biodiesel fuel originated from used cooking oil in a Renault Mégane automobile and four stroke, four cylinder, F9Q732 code and 75 kW Renault Mégane Diesel engine in winter conditions for 7500 km road tests in urban and long distance traffic. The results were compared to those of No. 2 diesel fuel. As a result of the No. 2 diesel fuel application, the engine injectors were normally carbonized. After the first period, as a result of the winter conditions and insufficient combustion, carbonization in the injectors was observed due to biodiesel usage. As a result of the second period, since the viscosity of the biodiesel was decreased, the injectors were observed to be cleaner. Also, no carbonization was observed on the surfaces of the cylinders and piston heads. The catalytic converter was plugged because of the viscosity in the first period. After the first period, an additional washing step was added to the biodiesel production procedure to reduce the glycerin content of the used cooking oil originated biodiesel, and the test was continued with low glycerin content biodiesel in the second period. Also, the commercial viscosity improver for No. 2 diesel fuel additive was added to the used cooking oil originated biodiesel (BDV). As a result of these modifications, in the second period, no problem was observed on the catalytic converter and injectors.

Dorado et al. [69] also worked to determine the feasibility of running a 10% waste vegetable oil–90% diesel fuel blend during a 500 h period in a three-cylinder, direct injection, 2.5L Diter Diesel engine. Carbon deposits and wear appeared normal, without visual differences between the engine fueled with diesel fuel or the blend. Additionally, Repeated measures analysis of variance showed that viscosity differences between each test and diesel fuel were not significant.

Peterson et al. [43] reported that, when a modified 1000 h EMA-based test was run on three Yanmar 3TN75E-S 15 kW diesel engines fueled with three different blends of hydrogenated soy ethyl ester (HySEE), there was an obvious difference in the amount of black deposits inside each engine. The 100% HySEE engine had little or no black soot visible in the oil pan, valve cover, or inside the case. In contrast, the 50% HySEE engine had more visible soot while the 25% HySEE engine clearly had the most. The oil analysis reports verify this trend. The reported F-Soot number roughly corresponded to the blend of HySEE in each engine. The 25% HySEE had the largest F-Soot number, while the 100% HySEE consistently had the lowest. They pointed out that the fuel setting on the 25% HySEE engine was found to be out of range after the test and more fuel was injected into this engine than the others. This would have caused more incomplete combustion than the other two engines and thus more soot. They also found that the trend from low soot to high soot did follow the trend from more biodiesel to less biodiesel for the three engines. Therefore, overfueling was not totally responsible for the higher soot, but probably made it worse. At the end of the 1000-h test, the injector pumps were evaluated and it was reported that, by the end of the test the 25% HySEE, engine's injector pump was overfueling the engine during high torque operation (1100 rpm) by nearly 25%. After thorough investigation, the bypass valve on the fuel filter housing was found to be defective for 25% HySEE engine. As for the investigation of main bearing, it was found that, at 820 h, the 100% HySEE engine experienced main bearing failure and started shutting down due to low oil pressure. This failure was thought to be due to the clutch becoming disengaged while the engine was running at full torque. The resulting overspeed compounded by an imbalance of the flywheel/clutch system caused the excessive wear in the two rearmost main bearings. At the time of the failure, all the main bearings were replaced and the engine was put back in the test cell to finish the test.

Gonzalez-Gomez et al. [55] evaluated exhaust emission and performance characteristics in a Toyota van, powered by a 2L IDI and NA diesel engine, operating on vegetable based WCOME. And they reported that, when using WCOME biodiesel, polymerisation of the lubricating oil did not occur, the viscosity was still in grade at the end of the trial by 2887 km, and the wear metals such as chromium, iron and lead were higher when the trial finished. It should be noted that the clean biodiesel, instead of diesel, was used as reference fuel.

3.5. Summary

Based on analysis above, the following conclusions are available:

(1) More or less reduction appears in power performance for pure WEO biodiesel due to the lower heating value, the higher density and viscosity, which lead to fuel flow problems, decrease combustion efficiency and lower thermal efficiency compared to diesel fuel. The power performance decreases with the increasing amount of WEO biodiesel in the fuel blend.
(2) Engine fuel consumption increases when using WEO biodiesel with regard to diesel, due to the lower heating value, the higher density and viscosity. BSFC increases with the increasing of WEO biodiesel percentage in the fuel blends.
(3) Thermal efficiency, inversely proportional to BSFC and heating value, decreases slightly or appears similar for WEO biodiesel. Other properties and characteristics of biodiesel also affect BTE, such as higher viscosity leading to minimizing the fineness of atomization, and higher oxygen content resulting in complete combustion.
(4) It is expectable that the use of WEO biodiesel could improve endurance performance of engine for biodiesel, compared

Table 4
Results of engine performances of WEO biodiesel compared to diesel.

Engine performances	Comparison result
Power performance	Lower
BSFC	Higher
BTE	Similar
Endurance performance	Better

with diesel. But the further studies on WEO biodiesel engine endurance tests need be executed, because the studies on these aspects are not enough so far.

Table 4 shows that the results of engine performances for WEO biodiesel compared to diesel.

4. Emissions of WEO biodiesel engine

4.1. PM

Almost all researchers, who carried out study on PM emis sion of WEO biodiesel, agreed that the pure WEO biodiesel results in reduction of PM emission compared to diesel [11,13,15, 27–30,39,41,46,47,49,53,55,56,59,62,66,70–72]. For example, Utlu and Koçak [47] measured that the smoke density was 34.8% for WFOME and 51.5% for diesel at the speed of 4000 rpm, respectively. And the decrease in smoke density was on average 22.46% for WFOME compared to diesel. Fujia Wu et al. [71] reported that different biodiesel (WME, PME, CME, RME and SME) reduced PM emission by 53–69% on average. Çetinkaya and Karaosmanoğlu [39] showed that the smoke reduction was in the range of 60% for B100, compared to diesel fuel. The more reduction was reported in [27], where PM decreased by 86.89% with use of the WPOME.

Unbelievable, Lin et al. [73] observed that the PM concentrations for B100 from wasted cooking oil were higher than other fuels (including diesel) for the tested engine speeds (1000 rpm, 1600 rpm, and 2000 rpm only). The authors had no suitable explanation but suggested that a biodiesel engine may not necessary to give a lower PM emission if the engine not in a well-tuned condition.

Higher oxygen content of WEO biodiesel is considered as the dominant factor of reduction in PM emission [11,13,41 ,48,56,62,64,68,74], compared to diesel fuel. Some researchers [13,28–30,39,41,46,53,58,62,64,70,74] reported that, PM emission reduces with the increasing of biodiesel content, which means better combustion due to more oxygen. In addition, lower or no sulfur content [39,48,62,68], lower or no aromatics [13,41,62,68], lower carbon content [39,62], slight advance in injection timing [29,41] and lower final distillation temperature [13,64] are also contributed to result in the reduction in PM emission.

Engine load [11,13,28,41,71,62] and engine speed [29,39,47,53 ,55,56,73] have a sufficient influence on PM emission for WEO biodiesel. Di et al. [62] showed a trend that PM emission of biodiesel increases with engine load and the reduction in PM emission of biodiesel increases with engine load. This trend was also proved in [11,28]. Ozsezen and Canakci [29] found that smoke opacity took place at very high level at the high engine speeds, especially at 2500 rpm and 3000 rpm, due to increased cylinder gas temperature caused by increased air turbulence and fuel oxidation under the high engine speed conditions. And Çetinkaya and Karaosmanoğlu [39] and Lin and Li [56] illuminated that PM emission of biodiesel reduced with engine speed as the result of more complete combustion.

In addition, effect of test condition and additives on PM emission has been surveyed for WEO biodiesel. Armas et al. [70] focused on the measurement and analysis of the smoke opacity resulting from a Diesel engine fuelled with conventional fuel and biodiesel from used cooking and unused vegetable oils under transient conditions, including engine start, load increase at constant engine speed and engine speed decrease at constant torque. The results suggested that the use of the diesel blends containing vegetable esters is an interesting alternative for a significant reduction in smoke opacity not only in steady conditions but also in transient engine operation. But the authors found that the advantage of biodiesel in PM emissions will be weakened or even reversed under cold start conditions, due to the fuel's higher kinematic viscosity and lower boiling point which make fuel atomization and evaporation more difficult. In the literature [41], alcohol were added into biodiesel from waste cooking oil and the further decrease in PM emissions was reported due to the enrichment of oxygen content in the fuel.

4.2. NO_x

Most of researchers agreed the conclusion that NO_x emission of WEO biodiesel is higher than that of baseline diesel fuel [11,27,30,45,46,48,49,55,56,62,63,65,66,71–73,75,76]. Fox example, Wu et al. [71] compared NO_x emissions of five biodiesels (CME, PME, SME, WME, and RME) and diesel fuel. And all five biodiesels result in higher NO_x emissions than diesel fuel, but the extent of the increase varies, ranging from 10% to 23% relative to diesel fuel. Ozsezen et al. [27] employed the WPOME and COME on a 6-cylinder WC, NA, DI diesel engine and found that the NO_x emissions of the WPOME and COME increased by 22.13% and 6.48%, respectively. Ulusoy et al. [49] NO_x emissions also increased by 5.03% as a result of biodiesel consumption, but the observed values were lower than the standards.

Some literatures [29,47,52,59,60] reported that NO_x emissions reduced when using WEO biodiesel. Roskilly et al. [52] NO_x emissions from the two trial engines when fuelled with biodiesel showed lower emission levels than that when fuelled with fossil diesel, he reductions of NO_x emissions are from 1.1% to 10.8% for Perkins engine and from 18.0% to 24.3% for Nanni engine over the load range, due to the smaller heating values and the higher cetane number of biodiesel. Utlu and Koçak [47] Occurring of NO_x was determined as 482 ppm for diesel fuel and 465 ppm for WFOME at 3000 rpm.

Of course, no difference or small difference was found between biodiesel and diesel in [31,41]. Sudhir et al. [31] reported that the NO_x emission of WEO biodiesel was negligibly higher than that of baseline diesel fuel. Though the combustion temperature and pressure is low for biodiesel operation, the NO_x emission is almost the same as that of diesel operation. This may be because of one of the interesting characteristics of the biodiesel, i.e. its oxygen content in its structure. Lapuerta et al. [41] found no significant differences between the reference fuel and any of the tested biodiesel fuels in NO_x emissions, they explain this trend according to the following arguments: (a) no noticeable differences in the adiabatic flame temperature, (b) there are very slight differences in oxygen content and (c) no appreciable differences in cetane number but slightly increasing cetane numbers with the number of carbon atoms of the alcohol, this leading to lower premixed combustion.

Many comparative tests have been studied to perform the effect of content of biodiesel on NO_x emissions [18,28,29,44,46, 58,64,68,74,75]. Many literatures [28,46,68,74] showed that NO_x emissions increase with the increase in content of biodiesel. Rao et al. [28] showed gradual increase in the emission of NO_x with increase in percentage of UCME in the fuel, when NO_x

emissions of diesel, 20%, 40%, 60%, 80%, 100% UCME biodiesel were compared. Behçet [46], Karavalakis et al. [68] and Lue et al. [74] all concluded that the increasing proportion of biodiesel in the blends causes the increased NO_x emissions. However, Leung [58] reported that, at idling stage, increasing biodiesel content would slightly reduce NO_x level while the NO_x level would be slightly increased or decreased under loaded condition, on a diesel generator.

Properties of biodiesel such as higher oxygen content, higher cetane number, advance in injection and combustion, have important effect on NO_x emissions for biodiesel according to the literatures collected in this work. Higher oxygen content in WEO biodiesel enhances formation of NO_x, which is accepted generally [27,28,30,48,54,56,64,71]. However, a few authors [77,78] thought oxygen content in biodiesel has no obvious influence in NO_x emissions increase. And Canakci [79] found that there is no significant difference in the oxygen amounts in the exhaust between the fuels, No.2 diesel fuel (no oxygen), No.1 diesel fuel (no oxygen), SME (10.97% oxygen in mass) and its 20% blend, and the NO_x emissions of the SME and 20% blend were increased by 11.2% and 0.6%, respectively, compared to the No.2 diesel, but the NO_x emissions less 6% for No. 1 diesel fuel than for No. 2 diesel fuel. Therefore, they suggested that more researches are required regarding the other properties of biodiesel and their effects on combustion and fuel system to give better explanations about NO_x increase.

Higher cetane number of biodiesel shortens ignition delay and thus combustion advances. Karavalakis et al. [64] applied this argument to explain why NO_x emissions increase for biodiesel, and this argument was also showed in [74]. However, the argument above is questionable. Higher cetane number will not only lead to burn early, but also lead to lower premixed combustion, which will lead to softer changes in pressure and temperature, thus it causes lower NO formation. Wu et al. [71] agreed the argument and contributed it to the difference in NO_x emissions between PME and WME biodiesels, which have almost the same oxygen content. Roskilly et al. [52] also contributed this argument to the NO_x reduction, when an experimental investigation of the application of biodiesel from recycled cooking fat and vegetable oil on small marine craft diesel engines was completed.

Advance in injection and thus advance in combustion for biodiesel affect NO_x emissions, as discussed above. Canakci and Van Gerpen [30] found that the SOI timing for biodiesel from soybean oil and yellow grease (SME and YGME) were advanced about 2.68° and 3.55°, respectively, compared to No. 2 diesel fuel, and Ozsezen et al. [27] observed that the SOI timing advanced 0.75 °CA and 1.25 °CA for WPOME and COME, respectively, compared to the PBDF. And they all concluded that the advanced SOI caused the increase in NO_x emissions. Other authors also agreed that NO_x emissions increased due to advance in injection [29,50,55].

Effect of iodine number on NO_x emission was investigated in [59]. Authors selected six different vegetable oil esters from used hydrogenated soy, coconut, rapeseed, mustard, safflower and commercial soy oil to represent a range of iodine numbers from 7.88 to 129.5. As iodine number increased from 7.88 to 129.5, the NO_x increased 29.3%. They also pointed out that fatty acids with two double bonds appeared to have more effect on increasing NO_x emissions that that of fatty acids with one double bond. This argument was accepted to explain the increase in NO_x emissions in [68].

Engine type and its operating conditions have something to do with NO_x emissions of biodiesel. Roskilly et al. [52] investigated the application of biodiesel (recycled cooking fat and vegetable oil) on two small marine craft diesel engines, and reported that the reductions of NO_x emissions are from 1.1% to 10.8% for Perkins engine and from 18.0% to 24.3% for Nanni engine over the load range. In [15], ten types of Department of Defense operated diesel engines were included in the test, including engines used for on-road, off-road, and portable power applications, to provide the biodiesel emissions data, and the test results showed that engine type had an influence on NO_x emissions under the same test cycle. In addition, from the results in [15], the different test cycles (FTP and US06) also caused the difference in NO_x emissions. Karavalakis et al. [68] conducted emissions and fuel consumption measurements under the New European driving cycle (NEDC) and the Artemis driving cycles, and reported that biodiesel application during the Artemis driving cycles did not change NO_x profile, however, the emission levels were higher than those of the NEDC. The highest NO_x emissions were observed for the Artemis Urban cycle. Those were 3.1–3.7 higher than equivalent emissions observed for NEDC.

According to mechanism of NO_x formation, engine load plays very important role in NO_x formation [11,28,41,44,50,54,62,63,71,80,81]. As load is increased, the overall fuel–air ratio increased which resulted in an increase in the average gas temperature in the combustion chamber and hence NO_x formation which is sensitive to temperature increases. This trend was illustrated in literatures [28,44,54,62]. However, Meng et al. [11] observed that in general there is a decrease in the $BSNO_x$ emission with increase in the engine load, although the NO_x emission expressed in ppm increases with engine load. The decrease of $BSNO_x$ emission with engine load is more obvious at light engine loads of 0.08 MPa and 0.38 MPa and subsequently, the level of $BSNO_x$ concentration becomes steadier. Murillo et al. [50] reported the decrease of NO_x emissions with the increased load, and contributed to the increase in turbulence inside the cylinder, which may result in a faster combustion and lower residence time of the species in the high temperature zones. Of course, Wu et al. [71] and Lapuerta et al. [41] found that there were no significant trends mentioned above for NO_x emission with the increased load.

Engine speed also affects NO_x emissions. Some authors [56,60] agreed that NO_x emissions reduced with an increase in engine speed. They analyzed that this trend was primarily due to the shorter residence time available for NO_x formation, which may be as the results of an increases both in the volumetric efficiency and flow velocity of the reactant mixture at higher engine speeds. Usta et al. [54] reported that, NO_x emission reduced slightly with an increase in engine speed at 50% load, but increased with engine speed at 75% and 100% load. Gonzalez-Gomez et al. [55] and Roskilly et al. [52] also illustrated the trend of the increasing NO_x emission with engine speed, due to the dependency of NO emissions on temperature. However, Utlu and Koçak [82] found that the increasing in NO_x was between maximum torque and maximum power speeds for WFOME and the reference diesel fuel, which depends on exhaust temperatures and rising of volumetric efficiencies. A complex NO_x formation is shown in [48]. It is obvious that the higher NO_x formations at 2000 rpm and 2500 rpm are a result of enhanced fuel–air mixing. At 1000 rpm, 1500 rpm and 3000 rpm, the tested fuels exhibit very close NO_x amounts compared to one another. At low engine speeds, the lower inlet air flow speed or turbulence level and less atomization ratio cause locally high combustion temperature. At the same time, the BSFC levels for biodiesel and blends are gradually higher than that of PBDF. This also increases combustion temperatures and causes higher NO_x formation. For the engine speed of 3000 rpm, the fuel line pressure increases and causes better atomization and results in higher NO_x formation since fuel line pressure determines the spray properties at the fuel injection time and can change the atomization ratio in the cylinder. The higher oxygen concentration in the biodiesel spray increases the oxidation at high engine speeds, which were indicated by a reduction of UHC and CO emissions, resulting in increased NO_x emissions.

Many researchers have explored approaches to improve NO_x emissions of biodiesel. Meng et al. [11] compared the effect of applying a biodiesel with either 10% blended methanol or 10% fumigation methanol on a 4-cylinder, NA, DI diesel engine at a constant speed of 1800 rpm with five different engine loads. The results indicated that, $BSNO_x$ emission decreases by 6.2% and 8.2% on average when operating on the blended mode and on the fumigation mode, comparing with operating on ULSD, except at the highest engine load of 0.67 MPa. They concluded that, the lower $BSNO_x$ emissions obtained from the use of biodiesel blended or fumigated with 10% methanol suggests a reduction of the combustion temperature and hence the cooling effect of the methanol is more dominating than the effect of the high oxygen content. Fuel emulsification and the use of NO_x inhibitor agents in fuel are considered to be effective in reducing NO_x emissions. In [32], the authors reported that the use of 50% EGR with TD50 fuel (the treated waste cooking oil biodiesel–diesel blend with 50/50 by volume) resulted in a 40%, 47.5% and 55% reduction in the NO_x emissions for 25%, 50% and 75% loads, respectively, tested on a four stroke WC, NA and DI diesel engine. Kannan and Anand [83] investigated the effect of injection pressure and timing on NO emission for WCO biodiesel on a single cylinder, 4-stroke DI diesel engine at a constant speed of 1500 rpm, and reported that the NO emission level increased with increasing injection pressure and timing. Authors in [60] investigated the engine performance and emission characteristics of the biodiesel from used soybean oil, characteristics of the biodiesel, the O/W/O (oil-droplets-in-water-droplets-in-oil) biodiesel emulsion, the O/W/O biodiesel emulsion that contained aqueous ammonia (NO_x inhibitor agents), and ASTM No. 2D diesel on a diesel engine. The experimental results show that the O/W/O emulsion has no significant reduction in NO_x emissions, compared to neat biodiesel. However, the existence of aqueous ammonia in the O/W/O biodiesel emulsion curtails NO_x formation, thus resulting in the lowest NO_x emissions among the four tested fuels.

4.3. HC

It is predominant viewpoint that HC emissions reduce when pure WEO biodiesel is fueled instead of diesel [11,12,15,27–31,41,45,46,49,59,62,63,65,66,71,72], except Al-Widyan et al. [53] reported that the ester/diesel fuel blends including 100%, 75%, 50%, 25% ester were superior to the baseline diesel fuel as far as unburned hydrocarbons are concerned. For example, Sudhir et al. [31] reported that the UBHC emissions were approximately 35% lower for Fresh oil biodiesel and WCO biodiesel operation compared to baseline petroleum diesel fuel operation. This reduction was attributed to the complete combustion of the fuel droplets. Meng et al. [11] illustrated a decrease of 36.8% in BSHC emissions upon replacing ULSD with biodiesel. Ulusoy et al. [49] reported that, HC decreased by 30.66% as a result of UFO biodiesel use. But the more decrease in HC emission were reported by Canakci and Van Gerpen [30], who found that the HC reduction was 46.3% for YGME compared with No. 2 diesel fuel, and by Wu et al. [71], who showed that different biodiesels (PME, WME, RME, CME and SME) reduce HC emission by 45–67% on average, compared with diesel fuel. On the other hand, Lertsathapornsuk et al. [63] reported that, in the case of B100 from WFPO, the average HC emission was about $25.11 \pm 0.03\%$ lower than diesel No. 2. And the lower reduction rate of 14.29% in HC emission was showed for WPOME biodiesel in [27].

The properties of WEO biodiesel are related to HC emissions. WEO Biodiesel involves higher oxygen content, which leads to more complete combustion [12,28,29,31,41,48,63,64,68,71]. Additionally, in the literatures [18,29,48,64,71,74], the decrease in THC emissions is attributed to the higher cetane number for WEO biodeisel. Higher cetane number of biodiesel could reduce the burning delay, which results in the THC emissions reduction [29,64].

Many authors [21,28,30,46,62–64,84] agreed that HC emissions decreases with increasing WEO biodiesel percentage in the blend. However, An et al. [44] found that, using B10, B20, B50 and B100 compared to ULSD, there was no linear correlation between the biodiesel blend ratio and HC emission on a Euro IV common-rail fuel injection diesel engine. The similar trend is shown in [12].

Effect of engine load is investigated in [11,18,28,31,41,62,63]. Among of them, Meng et al. [11] reported that the BSHC emissions decrease with engine load, and authors contributed to the increase in combustion temperature during higher engine load. The same trend is illustrated in [41]. However, Di et al. [62] reported that, although the HC emission decreases with increase of engine load, due to the increase in combustion temperature associated with higher engine load for ULSD, for biodiesel blended fuel including pure WCO biodiesel, the HC emission, instead of decreasing straightly with engine load, has a peak value at the engine load of 0.38 MPa during the whole load range from 0.1 MPa to 0.7 MPa. On the other hand, Lertsathapornsuk et al. [63] observed the different trend when the engine was powered by B50, B100, and No. 2 diesel at various engine loads. HC emissions increased as the electrical loads of the engine were increased in all types of fuels, as the result of the increase in fuel consumption at higher electrical loads.

Engine speed has an influence on the HC emission [29,48,53,73,74]. Canakci et al. [48] illustrated that, the HC emission of WFPO biodiesel increased with the increase of engine speed from 1000 rpm to 1500 rpm, but after 1500 rpm, the HC emission reduced gradually with the increase of engine speed because high engine speeds cause the increased inlet air flow speed or turbulence, which enhances the effect of atomization of the fuel in the cylinder, makes the mixture more homogeneous, and reduces UHC emission. The similar trend is shown with the use of WFPO biodiesel in [29]. However, the contrary trend is found in [53], where the increase of HC emission is illustrated for biodiesel from waste vegetable oils and its blends as the engine speed increased, compared to the baseline diesel fuel. And Lue et al. [74] also reported that the HC emissions for the three fuels (20%, 30% blend fuels of biodiesel from waste fryer vegetable oil, and diesel fuel) showed a steady increase as the engine speeded up.

4.4. CO

It is common conclusion that CO emissions reduce when diesel is replaced by pure WEO biodiesel [11,27–30,42,45–50,55,56,59,60,62,63,65,66,68,71,72,84].

Gonzalez-Gomez et al. [55] found that there were significant differences of approximately 64% between WCOME biodiesel and mineral diesel fuel, when tests were executed in a van powered by a 2 L IDI, NA diesel engine. Dorado et al. [42] showed a significant reduction in CO (up to 58.9%) for used olive oil methyl ester compared to diesel fuel. But the CO emission of the YGME was reduced by 17.8% compared to No. 2 diesel fuel in [30], and the CO emission from engine powered by B100 of WFPOEE and B50 were less by 18% and 14%, respectively, than that powered by No. 2 diesel in [63]. The lower reduction in CO emission was 9.52% with use of the WPOME, compared with PBDF in [27].

However, some authors reported that there was no difference in CO emissions between WEO biodiesel and diesel [31,41]. This is mainly attributed to too low emissions so that it cannot be identified.

It was surprising that a significant increase in CO emissions was illustrated for pure WVO biodiesel in [53], as the result of

poorest combustion performance of 100% ester being the heaviest test fuel.

The reasons of reduction in CO emission for WEO biodiesel are mainly contributed to the higher oxygen content [12,28,29,46,48,51,54,56,62,63,71,74] and the higher cetane number [18,46,48,63,71]. CO is predominantly formed due to the lack of oxygen, but as an oxygenated fuel, WEO biodiesel leads to better combustion of fuel resulting in the decrease in CO emission [12,28,41]. The higher cetane number, which means shorter ignition delay, caused longer combustion duration and increases complete combustion reaction regions [48].

With content of pure biodiesel increasing in blends fuel, CO emissions of blends reduce due to the increasing in oxygen content. This trend was reported in [12,18,28,30,46,48,58,62,64,72,74,84]. However, the authors in [44,50,73] did not agree that there exists this trend. An et al. [44] reported that the CO emission generally decreased with the increasing decreasing biodiesel blend ratio under low and medium loads (less than 50% load), and they contributed to the extra oxygen in the biodiesel and its blends, which further reduces the fuel air ratio, causing the flame temperature to drop very fast, resulting in a higher CO emission.

Different engine affects CO emissions. An experimental investigation of the application of biodiesel (recycled cooking fat and vegetable oil) was performed on Perkins 404C-22 and Nanni 3.100HE diesel engines in [52], the reduction in CO emissions for Nanni engine is more obvious than that of Perkins engine. Durbin and Norbeck [85] illustrated the effect difference of 7 types of diesel engines with use of 5 fuels including yellow grease biodiesel blend. In addition, the project results in [15] showed that over the range of vehicle/equipment types, emission factors could significantly vary depending on application or type of usage.

Engine load has been proven to have a significant impact on CO emissions [11,50,54,62,71]. Meng et al. [11] showed that BSCO emission decrease with engine load, because the higher combustion temperature promotes more complete combustion and hence less BSCO emission at higher engine loads. Di et al. [62] reported that there is an increase of CO emission for test fuels including WCO biodiesel when the engine load is increased from 0.08 MPa to 0.20 MPa, but a decrease of CO emission on further increase of the engine load. The higher combustion temperature at higher engine load contributes to the general decreasing trend. Authors in [50,71] also found that CO emissions decreased as load increased, but they increased slightly at heavy load or full load.

Some literatures showed the variation of CO emission for WEO biodiesel with engine speed. Lin et al. [73] reported that CO formation decreased with increasing engine speeds for WCO biodiesel, as the result of the better air–fuel mixing process and/or the increased fuel/air equivalence ratio with the increased engine speed. This trend is also illustrated in [54–56,60]. Roskilly et al. [52] found that the same trend of CO emission for WCO biodiesel on Nanni engine, but the different variation of CO emission appeared on Perkins engine. The CO emission decreased with the engine speed firstly, and then increased with the engine speed, decreased again with the engine speed. This similar trend is shown in [47]. But in [29,48], the CO emission increased with the engine speed during low speed range, and then decreased with the engine speed during mediums speed, afterward increased again with the engine speed. In addition, Lue et al. [74] reported that CO emissions increased in accordance with the engine speed when B30, B20 WFVO biodiesel blends and diesel were used on a small DI diesel engine.

Driving cycle also has a significant effect on CO emission. Nas and Berktay et al. [15] compared the emissions of many types of vehicles including low, medium and heavy duty engines, and found a significant difference in CO emission for test fuels, including YGA-B100, YGB-B100 and their blends, for different driving cycles such as FTP, US06, AVL-8 modes. Karavalakis et al. [68] illustrated the difference when emissions measurements were conducted for the New European Driving Cycle (NEDC) and the Artemis driving cycles.

As additives, methanol has an impact on CO emissions of WEO biodiesel. Meng et al. [11] compared the effect of applying a biodiesel from waste cooking oil with either 10% blended methanol or 10% fumigation methanol on a 4-cylinder NA DI diesel engine operating at a constant speed of 1800 rpm with five different engine loads. When operating on the blended fuel, the BSCO emission is higher compared with pure biodiesel, but is at similar level to that of ULSD. When operating on the fumigation mode, the higher increase in CO emission appears. Cheng et al. [18] found that, the refined WCO biodiesel blend fuel B′20, which has less methanol and impurities, gave the minimum amounts of CO emission, compared to B20 (crude biodiesel), B50 and diesel.

4.5. CO_2

Emission of CO_2, as the main component of greenhouse gases, is of interest because of the likelihood that they contribute to global warming. It was reported in [27,42,44,46,73], biodiesel resulted in fewer CO_2 emissions than diesel during complete combustion due to the lower carbon to hydrogen ratio. Dorado et al. [42] showed a significant reduction in CO_2 (up to 8.6%, excepting step no. 2, which presented a 7.4% increase) for used olive oil methyl ester compared to diesel fuel. But Ozsezen et al. [27] measured that slightly reduction (1.74%) of CO_2 emissions for WPOME biodiesel.

Some authors reported that CO_2 emissions have no significant change [11,31,48,59,60]. Usta et al. [54] found that, at partial loads (50% and 75%), the CO_2 emissions of the fuels were very close to each other. But at full load, the CO_2 emissions of the blend were higher than those of the diesel fuel due to the increase in the mass of fuel injected using the blend and better combustion with the fuel borne oxygen. The increasing trend of CO_2 emissions for WEO biodiesel are reported in [30,32,35,49,55,64,67,68,72,76,86], due to more efficient combustion. The literature [30] reported that the CO_2 emissions for YGME increased slightly by 1.2% compared to the No. 2 diesel fuel. And there were increase of approximately 7.5% in CO_2 emissions for WCOME biodiesel, compared to diesel fuel in [55]. In addition, some increases of CO_2 emissions were observed from 1% to 6% with UFOME blends (B20, B30 and B50) over all driving conditions in [68]. Ulusoy et al. [49] also founded an increase of 2.62% in CO_2 emission with biodiesel from used frying oil.

Of course, in the case of biodiesel, the higher CO_2 emission should cause less concern because of Nature's recovery by raising biodiesel crops. The literatures [87] evaluated the effect of WEO biodiesel on global greenhouse gas emissions through the life cycle of CO_2 emissions. And they pointed out that biodiesel would cause 50–80% reduction in CO_2 emissions compared to petroleum diesel.

4.6. Non-regulated emission

Generally, exhaust emissions of regulated pollutants are widely studied; however, limited and inconsistent data are showed for unregulated pollutants, such as polycyclic aromatic hydrocarbon (PAH) and carbonyl compounds, which are also important indicators for evaluating available vehicle fuels. For better understanding WEO biodiesel, PAHs and carbonyl emissions is listed with emphasis below:

4.6.1. PAH

Many studies have shown that WEO biodiesel can reduce PAH emission. Yang et al. [88] reported that, for most ringed-PAHs and total-PAHs, B20 (80% diesel and 20% methyl ester from waste cooking oil) has a 23.7% reduction in PAH emissions compared to diesel fuel. Ballesteros et al. [21] investigated 16 PAHs associated to the particulate matter of conventional diesel fuel, rapeseed methyl ester, waste cooking oil methyl esters, waste cooking oil ethyl esters and their conventional fuel blends on a diesel engine under two urban and extraurban modes. The use of RSM, WCOM and WCOE fuel blends decreases the amount of the total PAH emitted as compared with the conventional fuel. However, unlike the RSM there is no linear trend with biodiesel content for WCOM and WCOE, and the amount of reductions are lower than that of RSM. Mittelbach and Tritthart [65] measured PAH 10, denoted according to the sum of these 10 compounds including fluoranthene, pyrene, chrysene, benzo(*a*)pyrene, benzo(*k*)fluoranthene, benzo(*ghi*)pyrene, benzo(*b*)fluoranthene, anthanthrrene, perylene and indeno (1,2,3-pyrene), PAH 8, denoted according to the sum of these 10 compounds without fluoranthene and pyrene, and PAH carcinog, denoted by summing the compounds (chrysene, benzo(*a*)pyrene, benzo(*b*)fluoranthene and indeno(1,2,3-pyrene)), under FTP 72 test conditions on a Volkswagen diesel Rabbit powered by a 1.6 L 4-cylinder 4-stroke IDI diesel engine, and illustrated the less PAH 10, PAH 8 and PAH carcinog for biodiesel from used frying oil than that of US-2D diesel. Likewise, Yang et al. [89] found reductions in PAH emissions with a 20% v/v blend of WCOM and diesel fuel. The authors reported higher quantities of light molecular weight PAH with this fuel.

However, some authors found the increase in PAH for WEO biodiesel. Karavalakis et al. [68] reported that it is evident from the results that the application of UFOME blends (B20, B30, B50) led to higher PAH emissions, compared to those of ULSD fuel, with a common-rail direct injection diesel engine. Kulkarni and Dalai [90] stated in their bibliographic study about emission results with used vegetable oils, showed that PAH emitted with waste cooking oil methyl esters were higher than those with conventional diesel fuel.

PAH emissions are related to biodiesel properties and engine operation conditions. Chien et al. [91] analyzed the PM-associated PAH emitted with 20%, 60% and 100% v/v blends of a conventional fuel with WCOM and found a progressive reduction with the biodiesel content, and contributed to the oxygen in the fuel producing a more complete combustion with biodiesel. Aakko et al. [84] carried out the tests of the vegetable oil esters, such as rapeseed methyl ester (RME), soy bean oil methyl ester (SME) and used vegetable oil methyl ester (UVOME), on a Euro 2 emission level Volvo bus engine without a catalyst, with an oxidation catalyst and with a CRT particulate trap, and the major part of the PAHs was found in the semivolatile phase both in the tests without and with catalysts. The major part of the semivolatile phase PAHs were light PAHs, whereas heavier PAHs were found in the particulate phase. And the general reduction of 14 PAHs was more than 60% with the oxidation catalyst for the major part of the fuels. Using the CRT catalyst/trap the level of PAH compounds in the particulates hardly exceeded the detection limit, but the PAH level in the semivolatile phase was roughly the same as with the oxidation catalyst. The differences between the test fuels were difficult to analyse due to the low PAH emission level of this engine, especially in the tests with catalysts. It seems that the bioesters reduced the PAH emission level when no aftertreatment was used. In the tests without catalyst all fuels containing bioesters resulted in lower particulate and semivolatile phase PAH emissions than the EN590 fuel.

4.6.2. Carbonyl

Karavalakis et al. [68] showed the total 13 carbonyl compounds emissions for SME blends (B20, B30, B50), UFOME blends (B20, B30, B50), and ULSD fuels, and results indicated that the presence of the UFOME blends led to significantly higher emissions than the corresponding SME blends and diesel fuel. This phenomenon may be explained by the fact that the parent oil already had an amount of carbonyls and carboxylic acids. But Graboski et al. [66] conclude that aldehyde emissions from various biodiesels are not significantly different than aldehyde emissions from certification diesel fuel.

However, Peng et al. [92] reported that, total aldehyde emissions for B20 (20% waste cooking oil biodiesel and 80% diesel) and diesel fuels are in the ranges of 15.4–26.9 mg/bhp/h and 21.3–28.6 mg/bhp/h, respectively, and concluded use of biodiesel in diesel engines has the beneficial effect in terms of aldehyde emissions. Di et al. [62] reported that, for the unregulated gaseous emissions, generally, the emissions of formaldehyde, 1,3-butadiene, toluene, xylene decrease, however, acetaldehyde and benzene emissions increase, with use of biodiesel from waste cooking oil, compared to ULSD fuel. And Peng et al. [92] reported a 23% reduction on average in formaldehyde emission with an on-road testing project, in which 20% waste cooking oil biodiesel and 80% diesel fuel were used in the test.

The effect of biodiesel percentage in blended fuels is illustrated in [62]. The formaldehyde emission decreases with the addition of biodiesel. With the addition of biodiesel, acetaldehyde emission increases.

The effect of engine load is also reported in [62]. The authors showed formaldehyde emission is in general higher at higher engine loads. The formaldehyde emissions are 3.9 ppm, 1.0 ppm, 7.5 ppm, 53.8 ppm and 84.1 ppm, respectively, for engine loads of 0.08 MPa, 0.20 MPa, 0.38 MPa, 0.55 MPa and 0.67 MPa, corresponding to reductions of 73.7%, 95.7%, 81.1%, 44.9% and 23.4%, compared with ULSD. But the acetaldehyde emission reaches the peak value at medium loads.

In [15], from the charts about the weighted modal emission factors for carbonyl compounds formaldehyde, acetaldehyde, and acrolein for the Camp Pendleton bus, Ford F9000 tractor and the 250 kW generator, and the FTP weighted carbonyl emissions for the Humvee, it can be seen that mode 1 for the AVL 8-mode cycle is the most significant contributor to carbonyl emissions, similar to that seen for the organic carbon and elemental carbon. Mode 8 provides the second most significant contribution to weighted carbonyl emissions. For the portable generator 5-mode cycle, a more even distribution of the carbonyl compound emissions by mode is seen. In addition, the authors provided the relative contributions of formaldehyde, acetaldehyde, and acrolein for the Camp Pendleton bus, Ford F9000 tractor, 250 kW generator, and Humvee, respectively. For the Humvee and 250 kW generator, formaldehyde makes the largest carbonyl contribution for all test combinations. For the bus and F900, the distribution between formaldehyde and acetaldehyde is more evenly distributed with the relatively fractions differing depending on the specific test combination.

The effects of increasing mileages and maintenance practice on aldehyde emissions are insignificant for B20 and diesel fuels in [92].

4.7. Summary

Based on analysis above, the following conclusions are available:

(1) The WEO biodiesel results in reduction of PM emission compared to diesel due to the higher oxygen content, as well as lower or no sulfur content, lower or no aromatics, lower carbon content, slight advance in injection timing and lower final distillation temperature. PM emission reduces with the increasing of biodiesel content.

Table 5
Results of emissions of WEO biodiesel compared to diesel.

	Regulated emission					Non-regulated emission	
	PM	NO_x	HC	CO	CO_2	PAH	Carbonyl
Comparison result	Lower	Higher	Lower	Lower	Uncertain	Lower	Uncertain

(2) Most of researchers agreed the conclusion that NO_x emission of WEO biodiesel is higher than that of baseline diesel fuel, mainly due to higher oxygen content. Properties of WEO biodiesel such as higher oxygen content, higher cetane number, advance in injection and combustion, have important effect on NO_x emissions for WEO biodiesel, as well as engine type and its operating conditions.
(3) It is predominant viewpoint that HC emissions reduce when pure WEO biodiesel is fueled instead of diesel due to higher oxygen content and higher cetane number for WEO biodeisel. Many authors agreed that HC emission decreases with increasing WEO biodiesel percentage in the blend.
(4) It is common conclusion that CO emission reduces when diesel is replaced by pure WEO biodiesel, mainly due to higher oxygen content and higher cetane number. With content of pure biodiesel increasing in blends fuel, CO emission of blends reduces due to the increasing in oxygen content. Driving cycle, engine type and its operating conditions also have effect on CO emission.
(5) There exist the inconsistent conclusions, some researches reported that the CO_2 emission reduces for WEO biodiesel due to the low carbon to hydrocarbons ratio, and some researches indicated that it increases or keeps similar because of more effective combustion. But the CO_2 emission of WEO biodiesel reduces greatly from the view of the life cycle circulation of CO_2.
(6) Many studies have shown that WEO biodiesel can reduce PAH emission with regard to diesel. Carbonyl compounds emissions have discordant results for WEO biodiesel. Biodiesel properties, biodiesel percentage in blended fuels, driving cycle and vehicle type have important effect on non-regulated emission.

Table 5 shows that the results of emissions for WEO biodiesel compared to diesel.

5. Conclusions

In this work, biodiesels from waste edible oil were reviewed to summarize the effects on combustion characteristics, engine performance and emissions. Although there have always been inconsistent trends for WEO biodiesel combustion characteristics, engine performances and emissions according to the different tested engines, the different operating conditions or driving cycles, the different used biodiesel or reference diesel, the different measurement techniques or instruments, etc., the following conclusions could be drawn.

(1) The decrease in ignition delay, the advance in SOI timing and SOC timing appears in engine with WEO biodiesel, compared to diesel. The injection line pressures seem different between biodiesel and diesel. The maximum heat release rate decreases and the crank angle at which it takes place advances for WEO biodiesel, compared to diesel. The peak cylinder gas pressure of WEO biodiesel are slightly higher than that of the PBDF and the rate of pressure rise for diesel is higher compared to those of WEO biodiesel.
(2) More or less reduction in power performance and increase in fuel consumption for pure WEO biodiesel are accepted by most of researchers, compared to diesel fuel. But the thermal efficiency for WEO biodiesel decreases slightly or appears similar. Meanwhile, it can be concluded from the limited literatures that the use of biodiesel favors to improve endurance performance of engine.
(3) Almost all researchers, who carried out study on PM, HC and CO emissions of WEO biodiesel, agreed that the pure WEO biodiesel results in reduction of PM, HC, and CO emissions compared to diesel. However, most of researchers agreed the conclusion that NO_x emission of WEO biodiesel is higher than that of baseline diesel fuel.
(4) Some researches indicated that the CO_2 emission reduces for biodiesel as a result of the low carbon to hydrocarbons ratio, and some researches showed that the CO_2 emission increases or keeps similar because of more effective combustion. But in any event, the CO_2 emission of biodiesel reduces greatly from the view of the life cycle circulation of CO_2.
(5) The reduction in PAH emissions appears for WEO biodiesel, but carbonyl compounds emissions have discordant results for biodiesel, although it is widely accepted that, biodiesel increases these oxidants emissions because of higher oxygen content.
(6) It can be concluded that the blends of WEO biodiesel with small content by volume could replace diesel in order to help in controlling air pollution, encouraging the collection and recycling of waste edible oil to produce biodiesel and easing the pressure on scarce resources to a great extent without significantly sacrificing engine power, economy and emissions.

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